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THE PROTECTIVE CHARACTERISTICS OF PBI AND NOMEX COVERALLS IN JP-4 FUEL FIRES

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AIR FORCE MATERIALS LABORATORY

TECHNICAL REPORT AFML-TR-72-253

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FOREWORD

This report was prepared by the Fibrous Materials Branch, Nonmetallic Materials Division, and was initiated under Project Number 7320, "Fibrous Materials for Decelerators and Structures," Task Number 732002, "Fibrous Structural Materials." The work was administered under the direction of the Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, with Stanley Schulman acting as Project Engineer.

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The copper heat meters were developed by W. P. Behenke of E. I. DuPont DeNemours Corporation, Inc.

This report covers work conducted during the period of January 1971 through September 1971. The manuscript was submitted by the authors in April 1972.

AFML-TR-72-253

This technical report has been reviewed and is approved.

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ABSTRACT

Air Force flight suits made from PBI and Nomex fabrics were exposed to JP-4 liquid fuel fires to evaluate the thermal protection qualitites offered to flight personnel. The two fabrics were compared on the basis of flammability, mechanical, and comfort characteristics. Thermal protection provided by the two materials was based on the mean difference in per cent body area damaged for sixty flight suits when exposed to a JP-4 fuel fire. PBI allowed twenty-one point five per cent less damage when compared to Nomex. PBI fabric in addition to providing thermal protection, has been proven in a full scale wear test to be the most comfortable flight suit fabric tested by the Air Force Operational Commands.

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INTRODUCTION

Nonflammable fabrics are required for flight apparel for Air Force aircrews because of the fire hazards to which they are exposed. Fibers chosen must be capable of withstanding direct exposure to a JP-4 liquid fuel fire. The fiber must not contribute to the wearer's injury by burning, melting, or allowing heat from the flames to penetrate. An acceptable fabric must also be comfortable to the wearer, durable, and capable of being made into a functional garment.

This report is a statistical evaluation of the protective merits of coveralls made of PBI (polybenzimidazole) and Nomex® (an aromatic polyamide) for use by Air Force crewmen. Random samplings of the protective merits of PBI and Nomex fabrics have previously been made (References 1 and 2) under varied environmental conditions (cold, hot, humid, dry, etc.). In this evaluation, we attempted to limit the number of variables (e.g., temperature, humidity, wind, etc.) as much as possible. This meant large quantities of the two materials had to be tested in as short a time span as possible to provide consistent ambient conditions. To further normalize the data, we attempted to monitor the heat load transmitted to the mannikins by the candidate fabrics as they traversed the fire by mounting calorimeters near the mannikin's surface.

® Registered trade name of E. I. DuPont DeNemours Corporation, Inc.

Obviously, any candidate fabric must be nonflammable. This criterion met, the fabric must then maintain a thermal insulating layer between the skin and the flames without shrinking or breaking apart. Thermoplastic fibers cannot be used because the fiber substance forms a flowing molten mass which could cause severe burns. In addition, the fabric must prevent the heat from penetrating the fabric and burning the underlying skin.

Special consideration must be given to the problem of heat transmission through the fabric. Fabric construction plays an important role in blocking heat from direct flame contact. Past research conducted at the Air Force Materials Laboratory demonstrated that fabric thickness, air permeability or porosity, bulk density, and weave pattern all affect heat transmission through fabrics. Of all the fabric parameters studied, increasing the fabric bulk was found to be the most important in improving protection for a given fiber type (Reference 3). In summary, then, a thermally protective fabric should be made from thermally stable fibers that will not burn, melt, shrink, or transmit heat.

Similar tests to those covered in this report were conducted by the Air Force from August 1969 through March 1970 (References 1 and 2). Fabric construction and flight suit design were considered, and flight suits made from two layers of lightweight (2.8 oz/yd^2) nonflammable PBI fabric were found to provide the most protection. However, the double layer concept was considered impractical when considering both comfort for summer wear and suit fabrication. Fabric thickness and weight were also considered and, in general, the thicker and heavier the fabric, the better the protection.

In the final selection of a flight suit fabric for Air Force use, we must consider other critical factors. The fabric must provide comfort to the wearer, must be highly durable due to rigorous end use conditions, must provide a neat military appearance, and must be compatible with mission objectives. When all of the above factors are considered, finding a suitable fabric for Air Force flight suits is a formidable task.

SECTION II

EXPERIMENTAL TECHNIQUES

1. OBJECTIVE

The objective of this evaluation was to statistically determine the protective characteristics of PBI and Nomex flight suits in simulated aircraft crash fires. An attempt was made to keep the number of test variables low and consistent. Since a large number of variables is involved, an attempt was also made to obtain enough data that meaningful statistical techniques could be used for data reduction.

2. TEST FACILITY

The tests were conducted at the U.S. Army Natick Laboratories' Sudberry Annex, in Sudberry, Massachusetts. The fire pit is 30 feet long, 20 feet wide, and approximately 1 foot deep. A water impermeable base covers the bottom of the pit which is covered with several inches of sand and then with water to within several inches of the top. The mannikin carriage is supported by a steel rope approximately 0.75 inch in diameter, and is moved by a separate motor-driven steel cable across the long dimension of the pit. Two mannikins are suspended on the carriage in tandem and are kept behind a protective fire wall between tests (Figure 1).

Three steel rails divide the pit to maintain even fuel distribution. Twenty-five gallons of fuel are spread in the three sections, which is consumed in approximately 30 seconds burning time (Figure 2). At the pit

Figure 1. Mannikins and Carriage

Figure 2. Fire Pit and Fuel Pouring

entrance, a vertical cinder block wall with pneumatically operated doors was erected, which provides both a thermal barrier to prevent mannikin preexposure and a controlled starting point. After the 25 gallons of fuel is ignited, the intensity of the fire is monitored by a radiometer and appropriate recording equipment. The test director signals the start of the run (Figure 3) when the intensity of the fire reaches 1.5 cal/sq cm-sec. Mannikins, clothed in the candidate fabrics, traverse lengthwise of the pit at a rate of 10 feet per second, which provides a 3-second exposure (Figure 4).

When the mannikins emerge from the fire, a spray of water from a fire hose (Figure 5) is put up between the flame source and the mannikins to protect them from radiant energy from the fire. Personnel then remove the exposed mannikins from the carriage (Figure 6) and away from the fire, where they are photographed to record the damage incurred (Figure 7). Four copper heat meters are suspended at the sides of each mannikin, as shown in Figure 1, one pair knee high and the other at the waistline. The heat meters are described in Appendix I.

The mannikins are made of polyester resin-impregnated fiberglass, coated with white epoxy paint, and clothed in standard Air Force issue cotton T-shirts, boxer shorts, and a size 40 regular flight suit. These mannikins are commercially available and are fitted with rings in the shoulders for mounting on the carriage. The mannikin dimensions are approximately those of a size 38 man, but since its arms and legs are fixed in position, we had to use a size 40 suit when dressing the mannikin. The flight suit is designed in accordance with MIL-C83141, dated 11 February 1969.

Figure 3. Test Initiation

Figure 4. Mannikins Traversing Fire Pit

Figure 5. Mannikins Protected by Water Spray

Figure 6. Removal of Mannikins

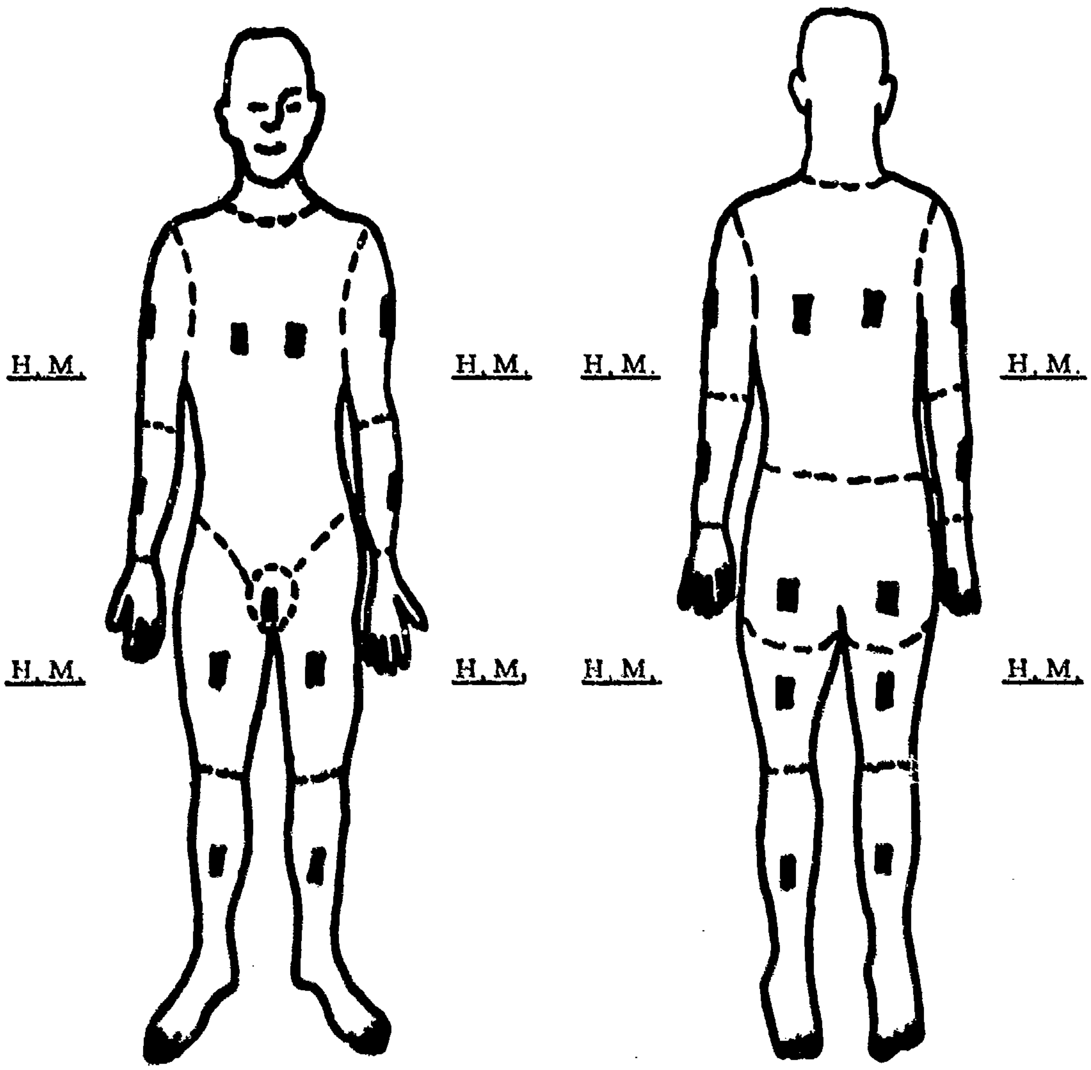
Figure 7. Photographic Record Taken Immediately After Exposure

type CWU-27/P. Nineteen temperature-sensitive paper strips are placed on the the mannikin's surface (Figure 8). The temperature indicators consist of organic pigments printed on black absorbing paper (Reference 5); when the pigment reaches its melting temperature it is absorbed into the paper strip. Damage is indicated when the sensors trip at 221°F, the approximate temperature where the skin blisters. The percentage of area covered by each sensor is shown in Figure 8 and was determined by the Brooke Formula (Reference 6).

When appraising the protection provided we considered only those areas covered by the flight suit; the hands, feet, head, and neck are excluded. Probably the most difficult part of full-scale fire-pit testing is trying to ensure a uniform exposure on both mannikins while providing an actual end-use environment with the full range of exposure possibilities. The thermal environment is highly variable: the radiant heat load to the mannikin can vary from 0 to 6.5 cal/sq cm-sec, depending on flame temperature and because a JP-4 fuel fire is a black body source. The convective component of a JP-4 fuel fire is dependent on fire velocity and temperature, and can vary from 0 to 1.1 cal/sq cm-sec (Reference 7). Each fire may consist of any combination of the above flux levels and, even if two mannikins are run in tandem, there is no guarantee that they will receive the same exposure. An attempt was made to normalize the data in three ways:

a. Mannikin Position

Mannikins were evaluated in pairs, mounted in tandem, and the position of the fiber types was alternated from front to rear on every other run. The test plan illustrating position of the Nomex and PBI



H.M. - Heat Meter Location

Body Area	Percentage	Body Area	Percentage
Anterior Trunk Right	6.5	Left Lower Arm	3.0
Anterior Trunk Left	6.5	Right Thigh Front	4.25
Posterior Trunk Right	6.5	Left Thigh Front	4.25
Posterior Trunk Left	6.5	Right Shin	3.5
Right Buttock	2.5	Left Shin	3.5
Left Buttock	2.5	Right Calf	3.5
Right Upper Arm	4.0	Left Calf	3.5
Left Upper Arm	4.0	Right Thigh Back	4.25
Right Lower Arm	3.0	Left Thigh Back	4.25
	Genitalia 1.0		

% damage X 1.27 to exclude hands, feet, neck and head.

Figure 8. Sensor Allocation

flight suits and the overall test sequence is provided in Table I. By running the mannikins in pairs, the fiber types could be compared by examining the resultant data from each fire separately.

b. Heat Meters

Wedge-shaped copper heat meters were placed close to each mannikin in four positions, as shown in Figure 8. The copper heat meters indicate the total heat by the temperature rise experienced by the mass of copper. Since the heat meters are static devices and do not provide a time-temperature profile, they cannot monitor rapid changes in cooling and heating within the fire. They merely indicate the total heat content for each exposure.

Damage to the fabrics is rate-dependent; if two suits receive 9 cal/sq cm total, one at a rate of 3 cal/sq cm-sec for 3 sec and the other at 4.5 cal/cm^2 -sec for 2 seconds and 0 cal/sq cm-sec in the third second, then the damage to the second suit could be more severe. Simply stated, if two samples receive the same amount of energy but at different rates, then the one that receives the energy at the lower rate could suffer the least damage. This premise is based on the fact that the materials do reach a temperature at which damage would occur. If a steady energy pulse is delivered to these meters, then the resultant data can be considered highly accurate. If the energy pulse is intermittent, then the data is subject to question. However, two facts favor the accuracy of the heat meter data: (1) the exposure time is very brief (3 seconds), thus the chance for many varied rates is slight, and (2) there appears to be excellent correlation between the amount of damage incurred by the suits and the heat meter readings.

TABLE I

Test Plan

Test No	Uniform Front-Rear	Test No	Uniform Front-Rear
1	PBI - Nomex	16	Nomex - PBI
2	Nomex - PBI	17	PBI - Nomex
3	PBI - Nomex	18	Nomex - PBI
4	Nomex - PBI	19	PBI - Nomex
5	PBI - Nomex	20	Nomex - PBI
6	Nomex - PBI	21	PBI - Nomex
7	PBI - Nomex	22	Nomex - PBI
8	Nomex - PBI	23	PBI - Nomex
9	PBI - Nomex	24	Nomex - PBI
10	Nomex - PBI	25	PBI - Nomex
11	PBI - Nomex	26	Nomex - PBI
12	Nomex - PBI	27	PBI - Nomex
13	Nomex - PBI	28	Nomex - PBI
14	Nomex - PBI	29	PBI - Nomex
15	PBI - Nomex	30	Nomex - PBI

c. Data Reduction Techniques

Even when a large number of variables are involved, if enough data is obtained and proper statistical techniques are employed, then an accurate assessment of the test data can be made. To achieve the desired accuracy for the fire-pit test as presently conducted we tested thirty suits of each fiber type. This requirement was established prior to installing the heat meters; these tests indicated that if the mannikins are run in tandem and reasonable methods are used to control the test variables, then perhaps testing half that number of suits could provide adequate data.

3. DAMAGE ASSESSMENT

Mannikin protection provided by the fabrics and damage sustained by the fabrics was assessed as follows:

a. Motion picture cameras are positioned on the left and front sides of the pit looking towards the exit. The films are analyzed for exposure conditions, including flaming and smoke generation of flight suits, after the mannequins exit the fire.

b. The condition of the suits immediately after exposure is recorded on 35mm slides, which are kept on file for reporting and data analysis purposes.

c. An extensive analysis of damage to the total ensemble is made by photographing each layer of clothing and describing it verbally (example photographs, Figure 9).

d. The temperature sensitive paper strips for each section of the mannikin are read and a rating of damage is assigned to each section of the mannikin as per Figure 8. Mannikin damage due to stains and dye transfer

Figure 9. Photographic Damage Assessment

is also considered. The data is recorded and an average percent body area damaged is calculated for each mannikin.

e. The four heat meters are cleaned of soot and the total heat content recorded by them is considered as an average heat load.

f. The final step is to conduct a statistical analysis of the recorded data, summarize the visual damage assessments and report the conclusions.

4. STATISTICAL TECHNIQUES

The statistical procedures used during this evaluation are described in Appendix II.

5. MATERIALS EVALUATED

Two fibers types were evaluated, PBI and Nomex. Polybenzimidazole (PBI) is an Air Force developed fiber produced by Celanese Research Corporation. Nomex is an aromatic polyamide produced by E. I. DuPont DeNemours and Company, Inc. The Nomex flight suits are standard Air Force summer weight flight coveralls (MIL-C-83141, dated 11 February 1969) type CWU-27/P. The PBI coveralls were designed to the same specifications as the Nomex coveralls.

SECTION III

RESULTS AND DISCUSSIONS

The two fabrics evaluated in this report were evaluated mainly for their thermal protection characteristics that could be used by Air Force personnel trying to escape from a burning aircraft. Because of the intended end use for these fabrics (i.e., flight suits) the fabrics also had to be evaluated for mechanical, comfort, and flammability characteristics. The following discussion was divided into the four categories mentioned above. Results for the first three topics - mechanical characteristics, comfort, and flammability characteristics - are outlined in Table II. The thermal protection characteristics are covered unar "Fire Pit Evaluation."

1. MECHANICAL CHARACTERISTICS

The mechanical characteristics of both fabrics are similar even though they are constructed somewhat different (Table II). Noticeable differences occurred in the abrasion data and strength data, both breaking and tearing. While Nomex was more abrasion-resistant, PBI had greater tearing and breaking strength. The operational wear test demonstrated that PBI fabric woven in an efficient construction has a service life at least as good as that of the currently used Nomex fabric and 3 to 4 times better than the formerly used cotton fabric (Reference 11).

2. COMFORT CHARACTERISTICS

One means of predicting the comfort characteristics of a candidate flight suit fabric is measuring the moisture regain (MR) which the fiber

TABLE II

Fabric Characteristics*

	PBI	NOMEX
Weight (oz/yd^2)	4.2	4.2
Thickness (mils)	14.3	12.1
Ends Per Inch	68	124
Picks Per Inch	59	83
Weave Pattern	2/1RHT	2/2 LHT
Moisture Regain (%)	12.0	5.0
Air Permeability ($ft^3/ft^2/min$)	124	99
Abrasion Resistance (cycles to destruction) (1)	1507	1945
Break Strength (lbs/in (2))		
warp	103	100
fill	97	66
Elongation (%)		
warp	19	34
fill	24	29
Tear Strength (lbs) (3)		
warp	20	17.5
fill	16.8	13.8
Flame Resistance (warp only) (4)		
flame time (sec)	0	0
glow time (sec)	1	9.8
char length (inches)	1	4.6

*All tests conducted in accordance with Fed Test Std No. 191

1. Emery Abradant Method #5308.1
2. Method #5104
3. Method #5134
4. Method #5903.1

exhibits. The MR of cotton is 8-10% at 72°F and 65% R.H.; of the two fabrics evaluated, PBI with an MR of 12% should and does provide better comfort than Nomex with its 5%. The higher MR characteristics of cotton and PBI are considered superior comfortwise, because they allow moisture to be transferred more readily than does a fabric with an MR of only 5%. When moisture is transferred through the fabric, it does not build up in the garment where it would cause a clammy feeling, but provides evaporative cooling on the outer surface of the fabric.

The moisture absorbing characteristics of a fabric is not the only criteria for measuring its comfort characteristics. Actually, the comfort offered by a particular fabric is generally determined by constructing garments and conducting a user evaluation, or wear test. This combines all the fabric characteristics that determine comfort (e.g., moisture regain, hand, air permeability, etc.). Full-scale wear tests have been conducted with flight suits fabricated from the two fabrics as outlined in Table II (References 8, 9, 10, and 11). The first two wear tests of Nomex coveralls conducted in 1965 and 1967 proved them to be unacceptable because they were too hot to wear and irritated the skin (References 8 and 9). In 1968, when they were again wear tested, they were adopted for Air Force use even though the Nomex suit was still considered warmer than the cotton K-2B flight suit (Reference 10). The adoption of Nomex flight suits into the Air Force inventory was considered a significant step forward in protection of Air Force personnel exposed to thermal hazards.

PBI flight suits were first subjected to a wear test in 1971 (Reference 11). When evaluated against standard issue Nomex flight suits, PBI obtained immediate acceptance by more than 85% of the users. A summary of the wear test reports for both Nomex and PBI flight suits is provided in Table III.

3. FLAMMABILITY CHARACTERISTICS

Flame resistance data, as obtained by the Flame Resistance of Cloth, Vertical Method No. 5903.1, is listed in Table II. Neither fabric continued to flame after removal of the ignition source which is held in contact with the bottom edge of a 2" x 12" fabric sample for 12 seconds. The Nomex fabric continued to glow for 9.8 seconds, while PBI glowed for 1 second. The resultant char lengths for the two fabrics showed the flame resistance of PBI (char length 1.0 inches) to be superior to that of Nomex (char length 4.6 inches).

TABLE III

Flight Suit Wear Test

TAC Test 65-93 (NOMEX)	TAC Test 67-215 (NOMEX)	TAC Test 68-211 (NOMEX)	OT&E (PBI)
500 suits	100 suits	20 suits	600 suits
Conclusions	Conclusions	Conclusions	Conclusions
Hot and uncomfortable, with related skin irritations	Warm and caused skin irritations.	Warmer than cotton K-2B, but not unbearable.	Rated superior to Nomex
Recommendation	Recommendation	Recommendation	Recommendation
Unacceptable	Unacceptable	Acceptable	Acceptable

4. FIRE PIT EVALUATION

A tabulation of the heat meter data is shown in Table IV. The average total heat data for each suit was calculated by averaging the heat content of the four heat meters. An indication of zero in the table was considered as such in the calculations, even though a zero could mean any value below 4.0 cal/sq cm since lower values could not be read accurately. (Referral to the calibration charts for the heat meters in Appendix I will illustrate the reason for this). This did not occur often and was not considered detrimental to the analysis. Where an asterisk occurs, the meter was knocked from its position during the test. When this occurred, the average was determined from those meters that remained in place.

All of the meters combined, for both the PBI and the Nomex flight suits, received an average total heat of 8.6 cal/sq cm, or an average heating rate for the three-second exposures of 2.9 cal/sq cm-sec. The average total heat data for the four positions around the mannikins showed that the upper meters received less heat than the lower ones and the front of the suit, on the average, received 0.6 cal/sq cm more than the rear of the suit. These slight differences indicate fairly uniform heating conditions from front to rear and a slightly decreasing heating profile from the bottom to top. These indications increase the reliability with which these meters can be used as a basis for comparing fabric performances in fire pit evaluations.

TABLE IV

Heat Meter Data
(cal/sq cm)

	FRONT SUIT					REAR SUIT				
RUN No.	U. L.	L. L.	U. R.	L. R.	AVG.	U. L.	L. L.	U. R.	L. R.	AVG.
1	6.2	5.8	4.2	6.2	5.5	0	6.4	4.2	6.0	4.2
2	8.4	8.0	9.6	8.0	8.5	6.4	6.4	8.8	7.2	7.2
3	4.8	9.2	8.8	14.0	9.2	0	4.0	4.8	9.2	4.5
4	0	6.6	4.4	7.2	4.6	4.6	5.8	4.8	6.6	5.5
5	8.0	9.4	9.8	12.4	9.9	9.2	9.6	16.0	13.2	12.0
6	7.0	7.0	7.2	8.4	7.4	0	7.2	9.0	7.0	5.8
7	9.2	11.4	11.0	11.0	10.7	9.0	11.4	8.4	10.4	9.8
8	8.8	9.2	7.6	8.8	8.6	7.6	9.0	5.0	7.6	7.3
9	4.4	8.0	0	7.2	4.9	4.6	6.6	4.8	8.2	6.1
10	9.2	7.8	9.8	7.4	8.6	6.4	8.0	7.0	8.2	7.4
11	4.2	7.0	4.4	0	3.9	4.4	5.8	5.0	7.2	5.6
12	6.4	7.2	7.6	10.4	7.9	0	6.0	0	7.2	3.3
13	5.6	5.6	6.4	8.4	6.5	5.4	6.0	8.2	6.0	6.4
14	0	6.2	4.8	8.4	4.9	6.0	7.2	5.6	7.2	6.5
15	14.0	13.0	4.4	5.0	9.1	12.4	10.0	7.0	11.6	10.6
16	4.0	5.8	6.2	7.4	5.9	4.0	5.6	5.0	5.4	5.0
17	0	6.4	0	5.8	3.1	5.8	5.8	4.6	6.4	5.7
18	6.0	6.4	6.0	8.4	6.7	6.0	6.2	6.0	6.2	6.1
19	9.2	10.4	9.4	11.4	10.1	8.2	9.0	11.4	12.6	10.3
20	13.4	13.2	14.0	12.8	13.4	13.6	14.0	14.2	15.4	14.3
21	9.6	8.4	9.6	8.2	9.0	6.4	7.6	8.0	5.6	6.9
22	10.0	8.4	5.6	7.6	7.9	13.6	12.2	6.2	10.0	10.6
23	13.6	12.8	13.6	12.4	13.1	16.6	13.6	15.2	14.2	14.9
24	14.4	14.4	6.0	8.0	10.7	13.6	14.2	7.0	7.6	10.6
25	14.2	13.6	7.8	8.6	11.1	12.6	11.8	13.9	13.0	12.8
26	10.4	13.4	12.6	12.6	12.3	8.0	10.0	14.0	10.0	10.5
27	10.4	10.8	9.0	11.0	10.3	10.4	10.8	10.4	11.0	10.9
28	16.8	*	26.0	*	21.4	12.0	*	10.0	*	11.0
29	7.0	6.0	8.0	7.0	7.0	8.0	8.0	5.6	6.0	6.9
30	13.4	8.8	12.4	14.0	12.2	12.0	11.0	11.0	12.0	11.5
Avg.	8.3	9.0	8.2	8.9	8.8	7.6	8.6	8.0	8.9	8.3

U. L. upper left
L. L. lower left
U. R. upper right
L. R. lower right
Position refers to mannikin's left or right hand. Lower meters were placed slightly above mannikin's knees. Upper meters were placed even with Velcro waist fasteners.
*No meter in this position.
** For odd numbers PBI suit is in front position, for even numbered runs Nomex is in front position

The per cent body area damaged for each mannikin is listed in Table V. The numbers appear highly variable, but when these data are related to heat data from Table IV the variations are found to be directly related to the amount of energy received during a particular exposure.

Table VI shows the frequency of damage to each of the 19 sensor locations to determine which areas receive the highest heating loads where additional protection might be needed. Additional protection might be provided by adding fabric to the present uniform or by modifying the suit configuration. From this analysis, it would seem advantageous to provide added protection for the extremities. The practicability of doing this would have to be considered by the suit designers for fabrication and by aircrew personnel for comfort and mobility.

The statistical analysis techniques used for the data reduction are defined in Appendix II. Briefly, an estimate of the mean for the per cent body area damage for each fabric type along with an estimate of the related standard error and the 90% confidence intervals was determined. Then the mean difference between the resultant damage for each fabric type was determiend by three difference methods. Method (a) is simply the average of the observed differences in percent body damage for thirty evaluations. Method (b) was similar to the first method except that those evaluations in which the heat meter readings between the front and back of the suits differed by more than 3.0 cal/sq cm were eliminated. This meant eliminating three runs, In method (c) once again the mean difference is determined but this time the bias introduced by the influence of the heat meter data of each suit is considered. The results of the statistical analysis are given in Table VII.

TABLE V

Per Cent Body Area Damage

3 Second Exposure		
Test No.	Uniform	
	Nomex	PBI
1	15.9 (%)	3.8
2	50.5	19.1
3	7.0	17.8
4	27.9	5.4
5	59.7	46.1
6	60.3	19.1
7	62.9	22.5
8	45.4	41.3
9	27.3	18.1
10	59.7	12.1
11	20.3	24.1
12	35.6	1.3
13	35.2	0.0
14	33.7	5.4
15	61.3	40.3
16	17.8	4.4
17	32.1	2.5
18	42.5	1.3
19	60.6	38.7
20	89.9	72.7
21	26.7	19.1
22	55.9	12.7
23	83.8	68.3
24	78.1	44.8
25	77.5	66.7
26	66.7	34.3
27	57.8	63.2
28	92.1	64.5
29	31.7	29.2
30	76.8	51.8
Avg.	49.8	28.4

TABLE VI

Frequency of Damage Occurrence

	PBI	Nomex
Anterior Trunk Right	12	10
Anterior Trunk Left	10	10
Posterior Trunk Right	9	18
Posterior Trunk Left	10	18
Right Buttock	10	20
Left Buttock	12	25
Right Upper Arm	10	20
Left Upper Arm	16	27
Right Lower Arm	14	23
Left Lower Arm	23	30
Right Thigh Front	21	25
Left Thigh Front	16	26
Right Shin	11	16
Left Shin	5	20
Right Calf	19	25
Left Calf	19	27
Right Thigh Back	14	25
Left Thigh Back	16	25
Genitalia	6	12

*Totals include partial damage where a per cent of an area was assigned because of staining or partial damage to sensor.

TABLE VII

Statistical Analysis Results

Parameter	Estimate	Estimated Standard Error of Estimate	90% Confidence Interval
Mean in percent mannikin damage for Nomex	49.8	4.25	49.8 ±7.2
Mean in percent mannikin damage for PBI	28.4	4.20	28.4 ± 7.1
Mean difference between Nomex and PBI in percent mannikin damage			
Method a.	21.4	2.83	21.4 ± 4.8
Method b.	21.9	2.85	21.9 ± 4.9
Method c.	20.5	3.61	20.5 ± 6.2

In the analysis of the protective characteristics of the fabrics, the fire resistance of the materials must be considered. If the fabric continues to burn after removal from the fire, then the wearer would continue to be burned even after escaping from the fire.

The flame resistance of the two candidate fabrics as evaluated in the fire pit is depicted in Figure 10. The front suit is Nomex, which emerged from the fire in flames and continued to burn to the point where fire extinguishers had to be used. The second suit is PBI, which did not burn in any test.

The following is a summary of the damage incurred by the uniform, underwear, and mannikin with each of the two fiber types. Although a verbal description for all 60 suits was recorded at the time of the evaluation, a restatement of each description taken would be highly redundant.

a. PBI-4.3 ox/yd^2 Fabric

(1) Uniform. The entire uniform was intact in all cases. Areas of the fabric were stiffened, scorched, or charred and shrunken. The Nomex hand covers and the Nomex booties were in most cases destroyed.* Areas of the uniform where a high incidence of damage occurred were at the lower portions of the extremities, buttocks, back and front of both thighs, and the lower trunk.

(2) Underwear. Light yellow to brown staining, light to moderate scorching or charring. When scorching or charring did occur it was in the form of streaks or random spots.

* Nomex hand covers and Nomex booties were used to cover the hands and feet of all 60 mannikins evaluated.

Figure 10. Front Suit Nomex, Rear Suit PBI

(3) Mannikin. Some light to moderate yellow to light brown staining. Several mannikins lightly scorched.

b. Nomex-4.2 oz/yd^2 Fabric

(1) Uniform. The suit emerged from the fire pit in flames which in some cases, had to be extinguished. The remaining area of the fabric was stiffened, scorched, or charred and shrunken. The Nomex booties and hand covers were generally destroyed.

In most cases, the entire portion of the uniform from the waist down both back and front, was badly damaged, as were the uniform sleeves.

(2) Underwear. Light to heavy green staining, scorched or charred, and partially destroyed. In several cases the underwear ignited and had to be extinguished.

(3) Mannikin. Light to heavy green staining with light to heavy scorching on the lower back portion, shins, and upper extremities.

Photographs depicting the damage received by the two types of fiber are shown in Figures 11-18. These photographs illustrate damage incurred by the two suits with similar exposure levels within a given run. Figures 11 and 12 show the damage to Nomex and PBI uniforms at an exposure level of 6.7 cal/sq cm and 6.1 cal/sq cm, respectively. The remaining figures show the damage level for suits that received from 9.8 cal/sq cm to 12.3 cal/sq cm (Figures 13 through 18). The lesser exposure as shown in Figures 11 and 12 had little effect on the PBI ensemble, while it did cause severe damage to the Nomex uniform. Slight shrinkage occurred in the PBI uniform while severe shrinkage occurred in the Nomex uniform. Other photographs show that the Nomex uniforms received a great deal more damage than did the PBI uniforms. In general, the underwear suffered more damage under the Nomex uniform than under the PBI uniform.

Figure 11. Run No. 19, Nomex Uniform

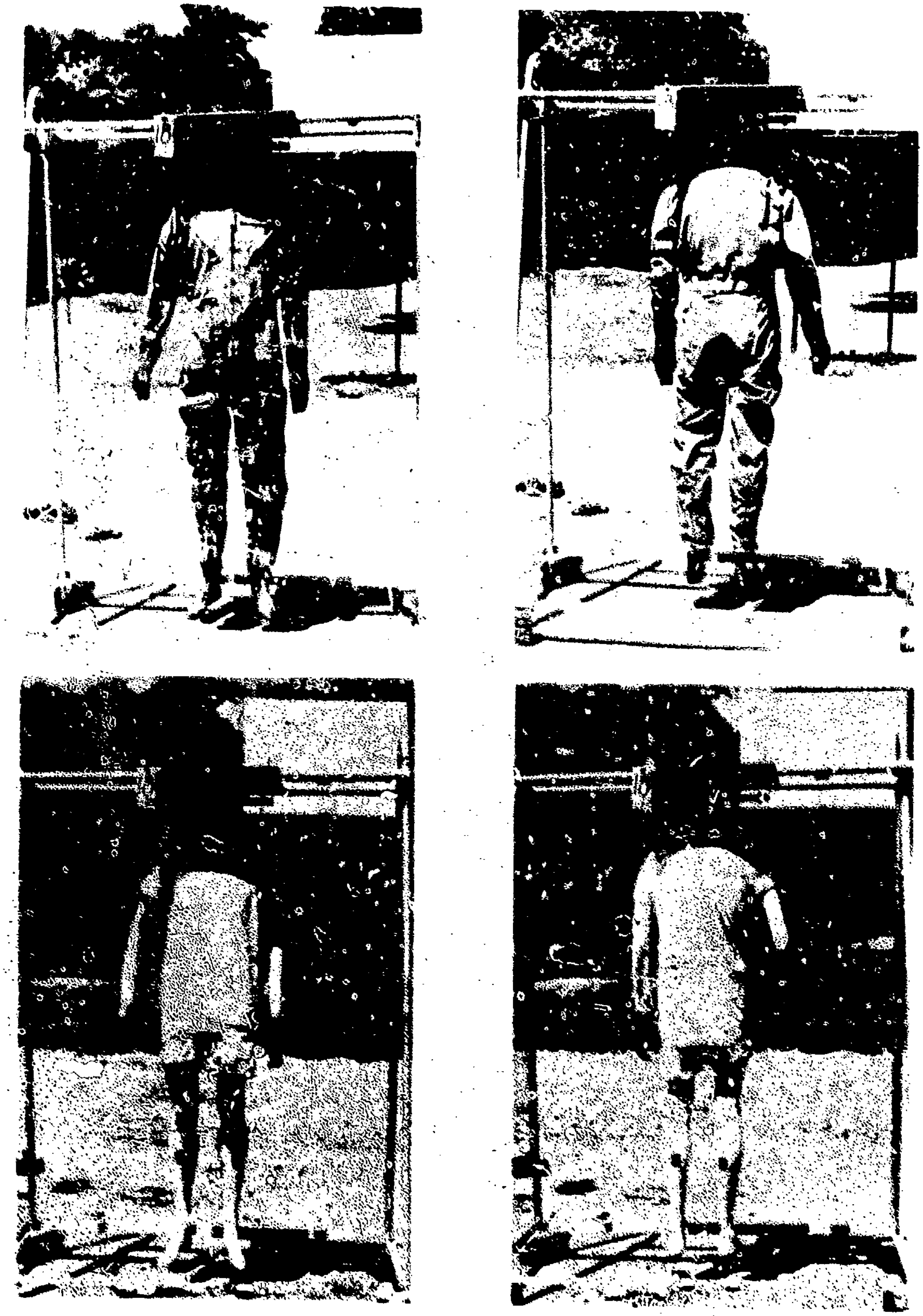


Figure 12. Run No. 19, PBI Uniform

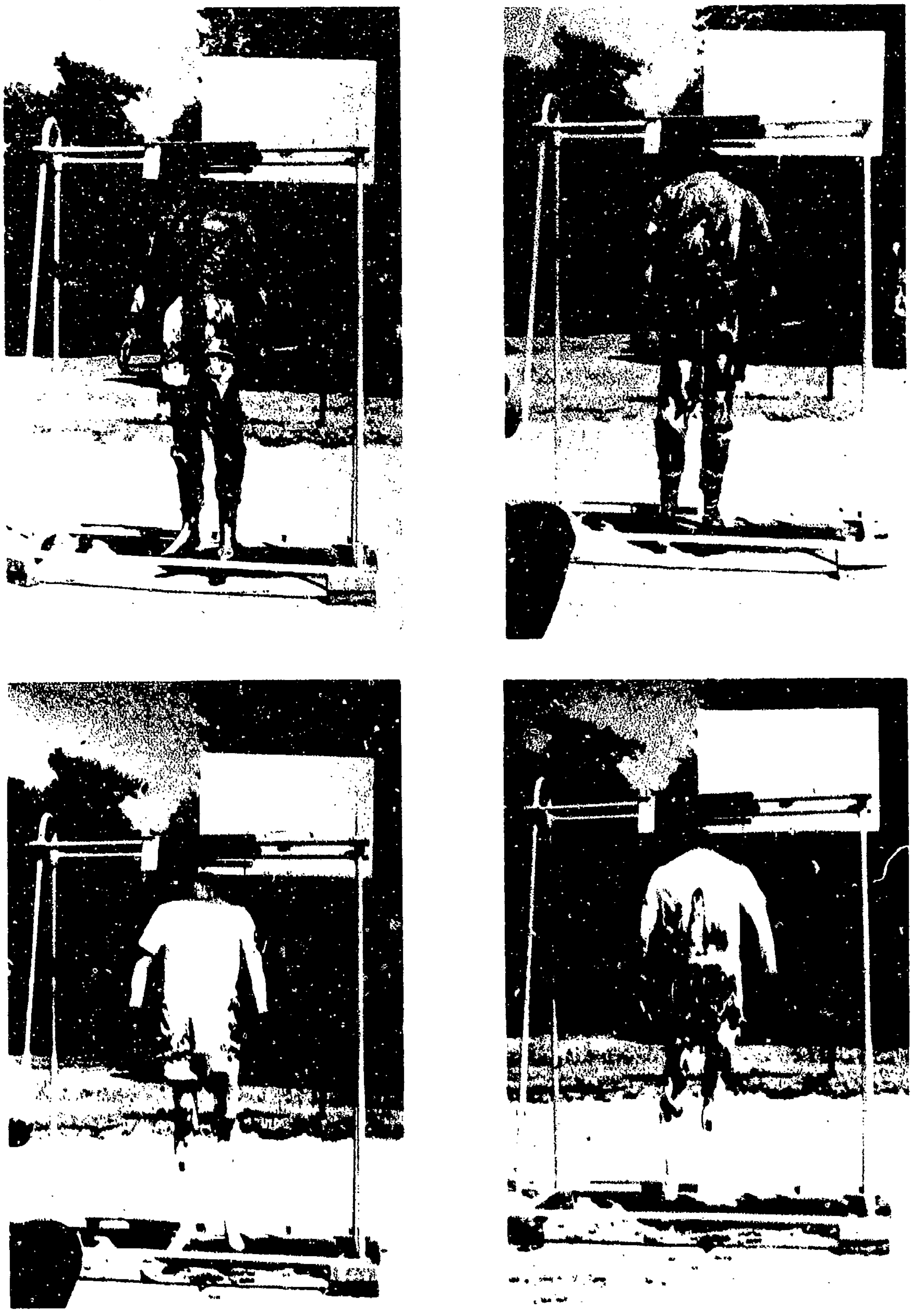


Figure 13. Run No. 7, Nomex Uniform

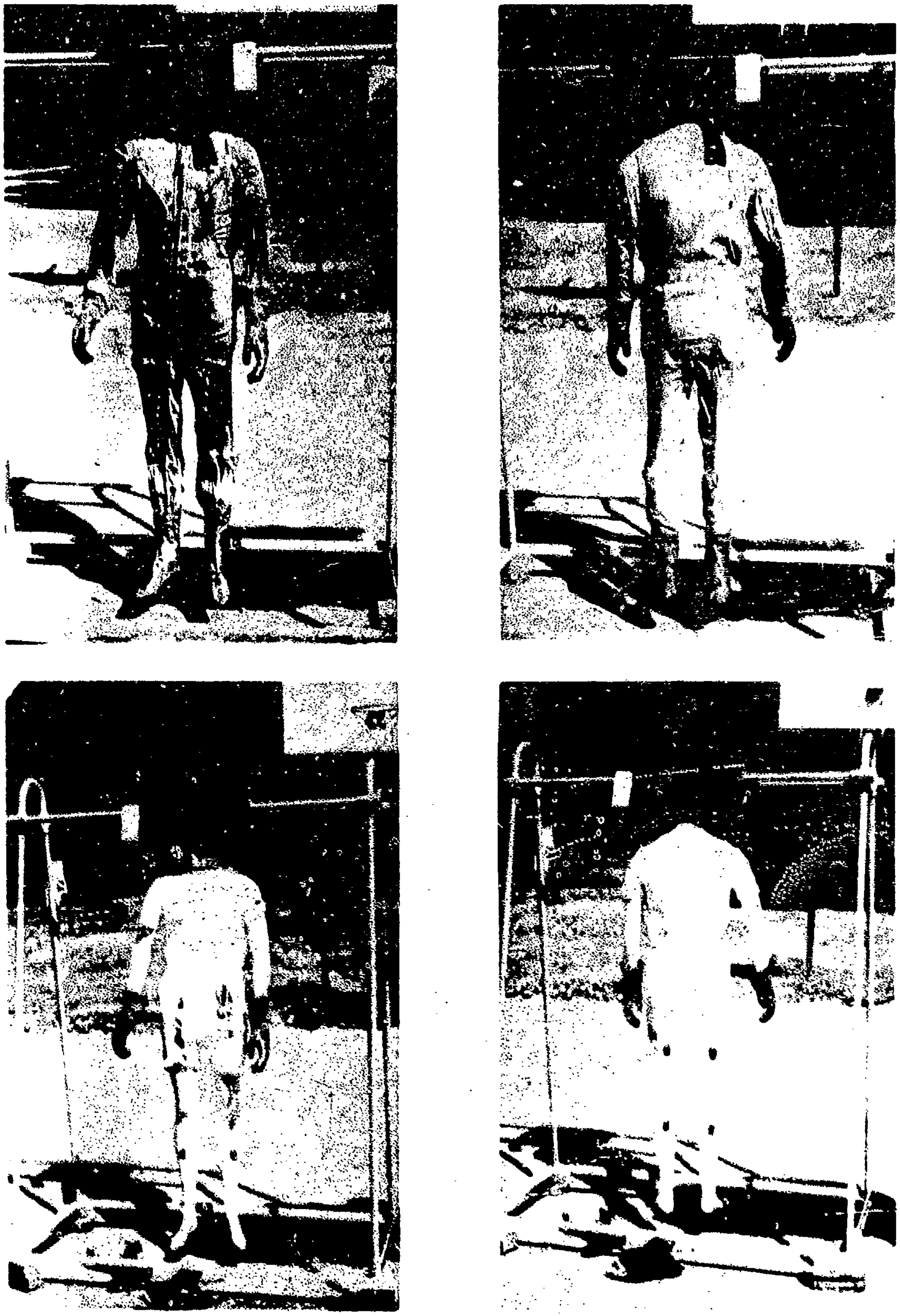


Figure 14. Run No. 7, PBI Uniform

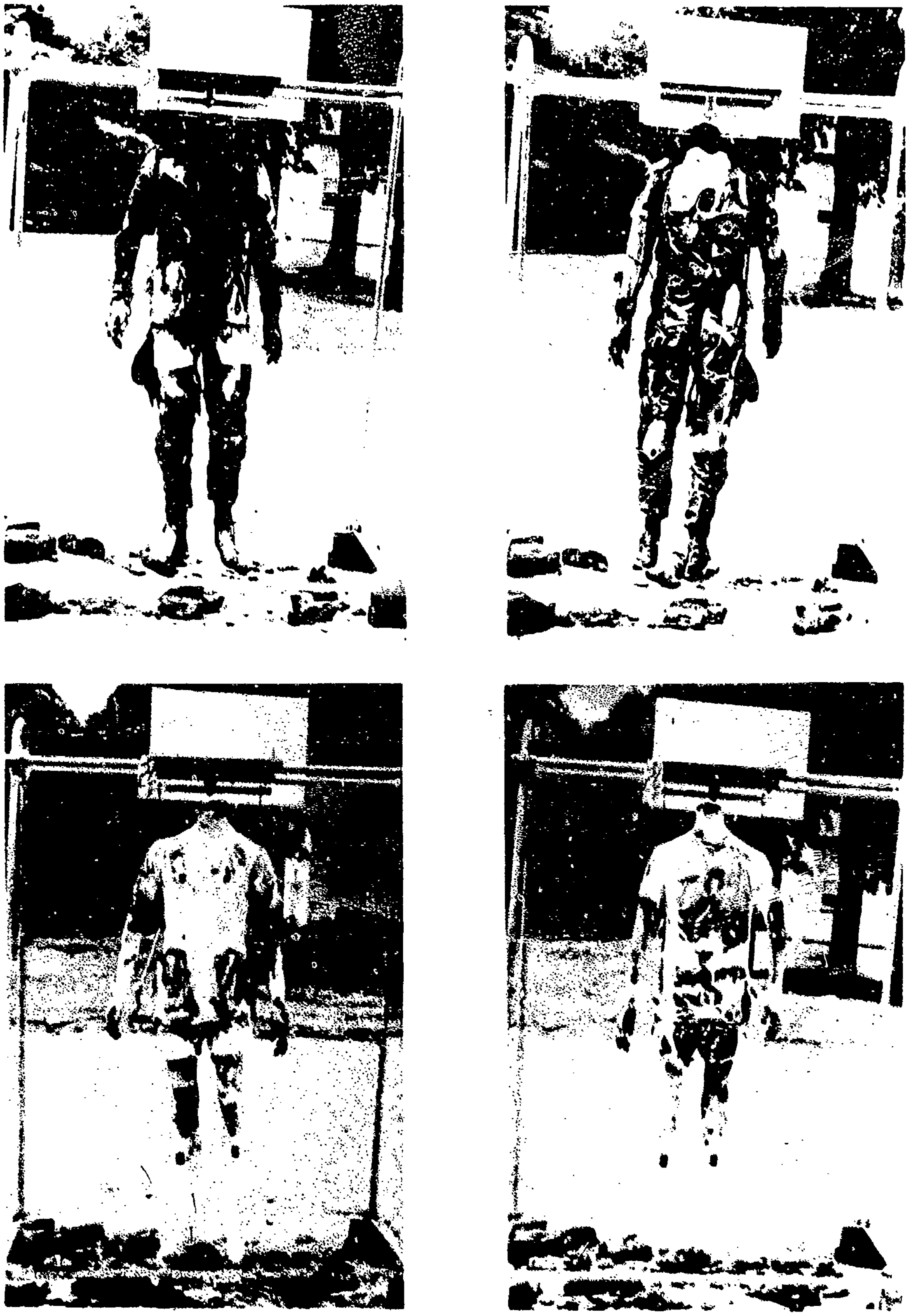


Figure 15. Run No. 26, Nomex Uniform

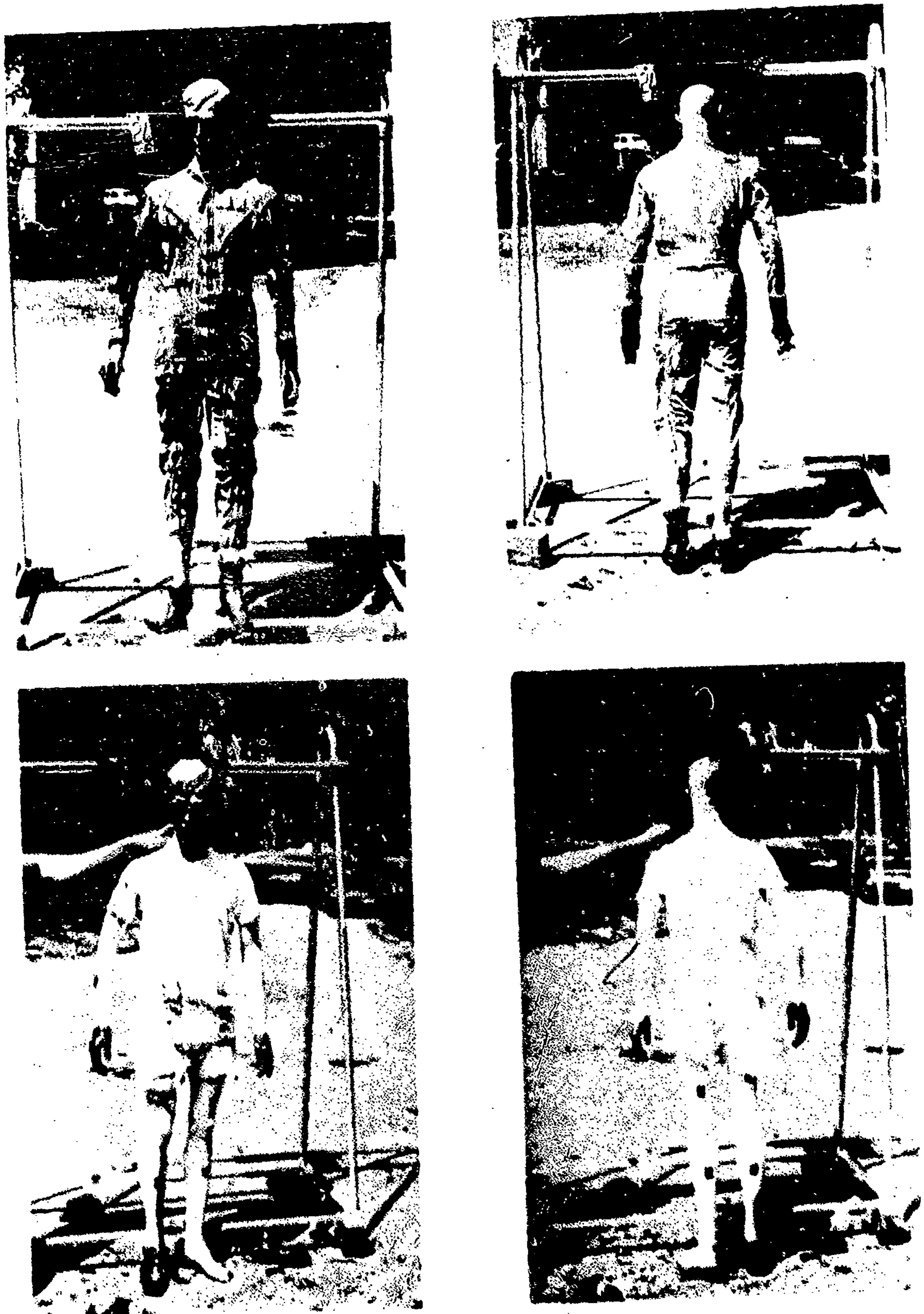


Figure 16. Run No. 26, PBI Uniform

Figure 17. Run No. 27, Nomex Uniform

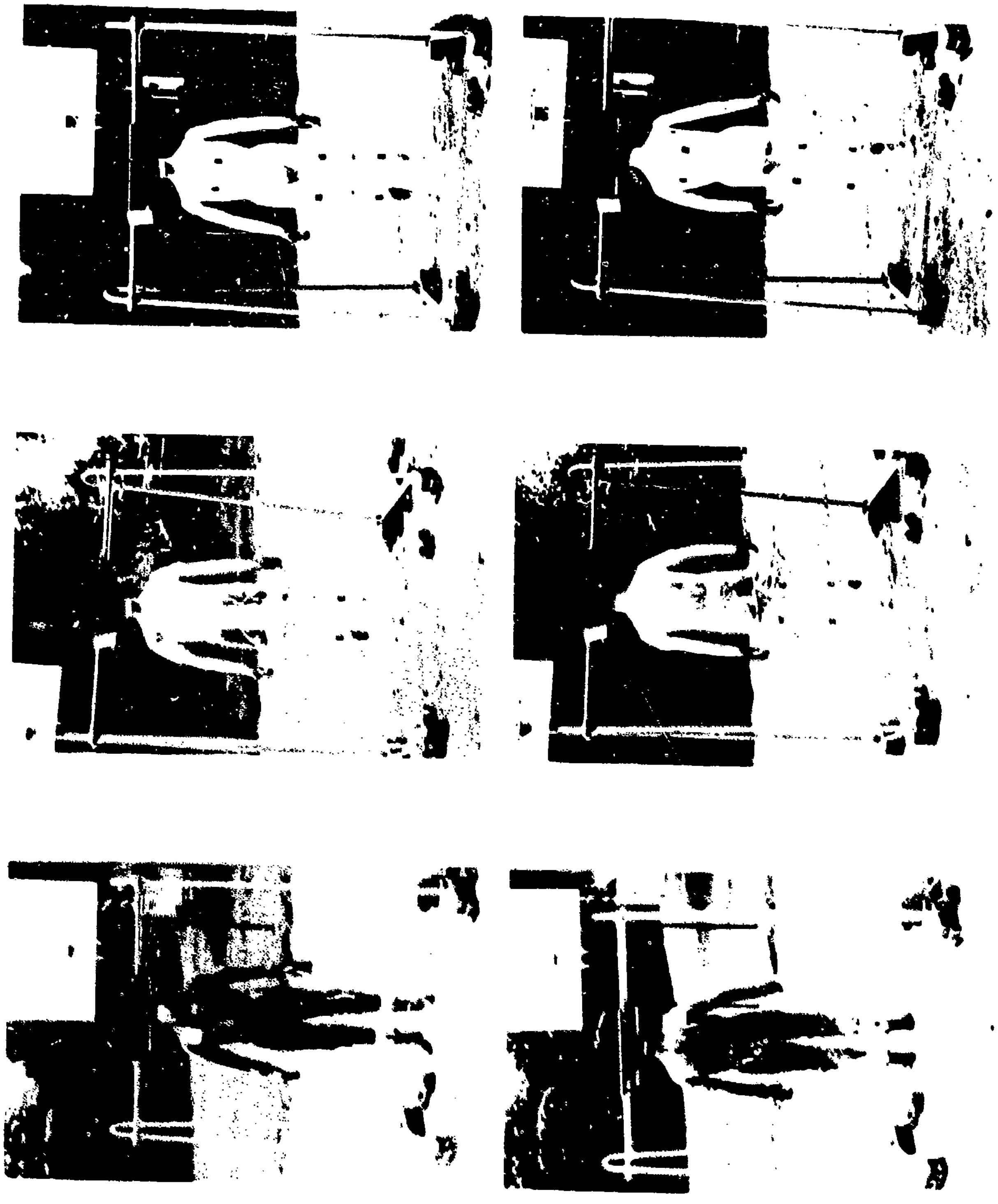


Figure 18. Run No. 27, PBI Uniform

SECTION IV

CONCLUSIONS

It has been demonstrated that PBI uniforms provide greater thermal protection than Nomex uniforms when exposed to JP-4 fuel fires. Based on the mean difference in percent body area damaged, Nomex flight suits allowed 21% more body area to be damaged than PBI flight suits.

PBI was nonflammable in both the vertical flame test and the fire pit evaluation. Nomex fabric did not continue to propagate flames in the vertical flame test, but did continue to burn after exposure to a JP-4 fuel fire, so that the fire had to be extinguished.

PBI demonstrated the nonflammability and protective qualities required for Air Force flight suits. In addition, flight suits constructed of PBI are more comfortable than those made of Nomex and have the mechanical characteristics necessary to provide a durable and functional flight suit.

Flight suits constructed of PBI should replace the present standard Nomex coverall. Steps should also be taken to consider using PBI fabrics for other Air Force applications where nonflammable fabrics are needed to protect Air Force personnel.

APPENDIX I

COPPER HEAT METERS

COPPER HEAT METERS

AFML fabricated the copper heat meters from copper alloy #110 as described herein. The temperature-sensitive paint strips were applied by masking the wedges to the desired stripe width and then applying the paint. The back face of the wedges was coated with high temperature, low reflectance (<3%), black epoxy paint (Mor-An-Tuff, 109-B-100/109-C-333).

Calibration consisted of exposing the black surface of the wedges to the top surfaces of three meker burners. The burners were mounted in tandem to provide a convective heating source across the full surface of the wedge. The energy output of the burners was monitored with a Hy-Cal Engineering total heat flux transducer. Time intervals and flux data were recorded with Moseley 135A X-Y recorder. The calibration curves are given in Figures 19 and 20.

After exposure to a JP-4 fuel fire, the meters were covered with soot deposits. They were cleaned with a mild rubbing compound and water, and then the length of the color change was measured. When two paint stripe readings of different temperature levels overlapped, then an average of the two readings was taken. The overlapping area where a reading could be taken from either paint stripe was from 8 cal/sq cm to 14 cal/sq cm. The two readings on an individual wedge did not vary more than 0.5 cal/sq cm, and in most cases the readings in the overlapping range were identical.

The design of the copper heat meters was based on the following principle.

The quantity of heat (H) is proportional to the area of exposure (A), mass (m) and heat capacity (C_p) of receiver, and temperature change (Δ T).

$$H\ (\mathrm{cal/cm^2}) = \frac{m\ C_p\ \Delta T}{A}$$

$$m = \text{area x thickness x density} = A\ d\ p$$

$$\therefore\ H = \frac{\cancel{A}\ d\ p\ C_p\ \Delta T}{\cancel{A}} = K\ d\ \Delta T$$

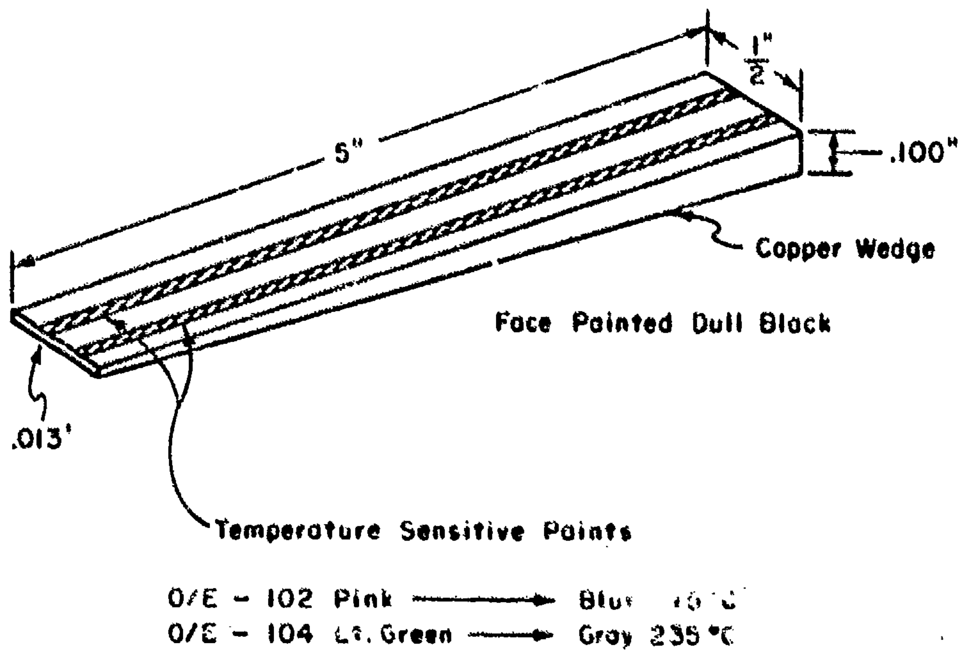


Figure 19. DuPont Heat Sensor

Thus, if the heat sensor is in the shape of a wedge, the heat content of an exposure is indicated by the thickness of the material where a known temperature change occurs.

The wedges are painted with stripes of "Thermindex" temperature indicating paints (Tempil Corp.) O/E - 102 and O/E - 104, which change color at 115°C (pink to blue) and 235°C (greenish white to gray), respectively. The wedge is calibrated with a known source using an insulator to expose only one face, and the above expression applies. If the sensor is exposed bare, the receiving area is approximately double and the sensitivity is 2 times the single face exposure.

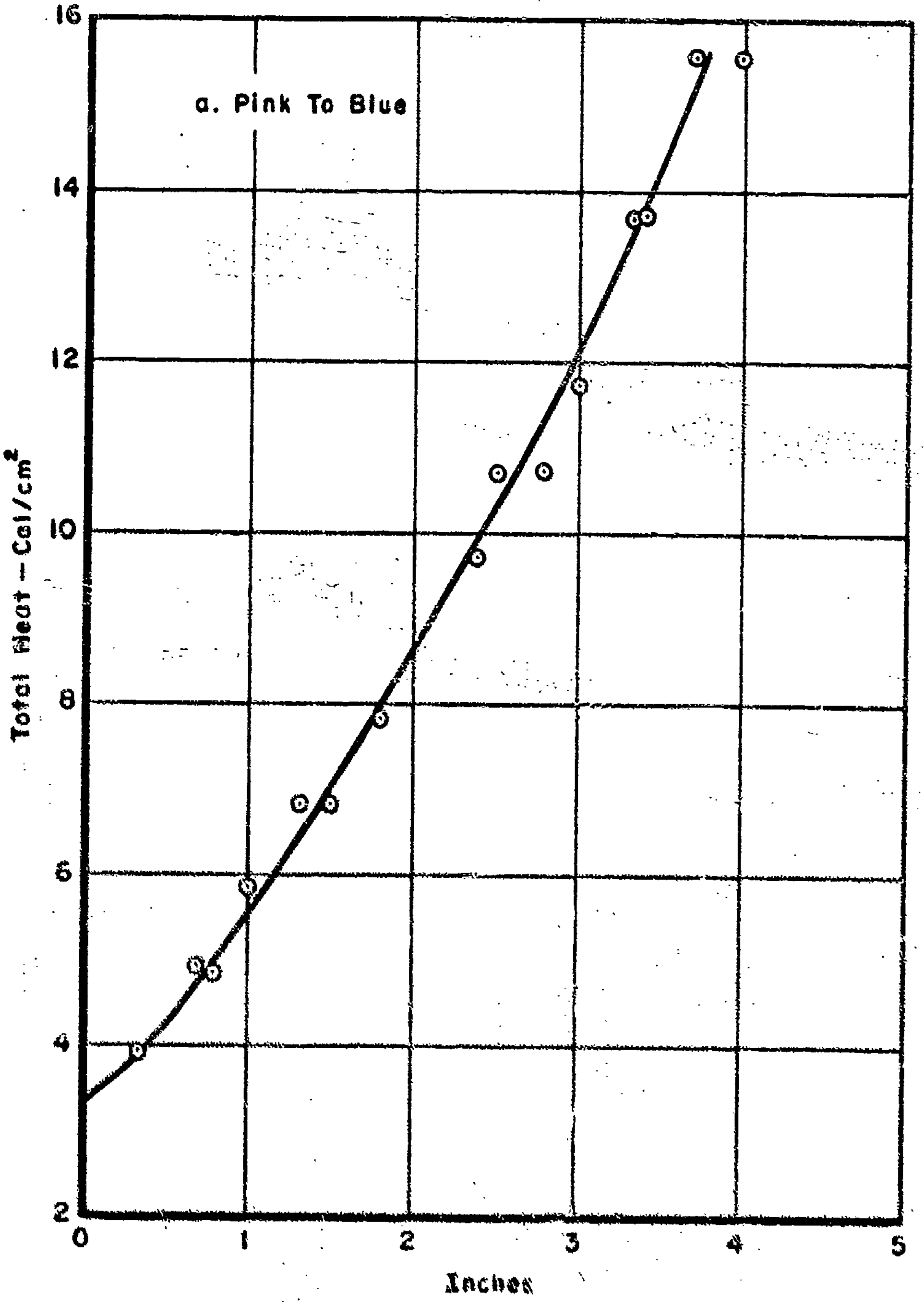


Figure 20. Heat Meter Calibration

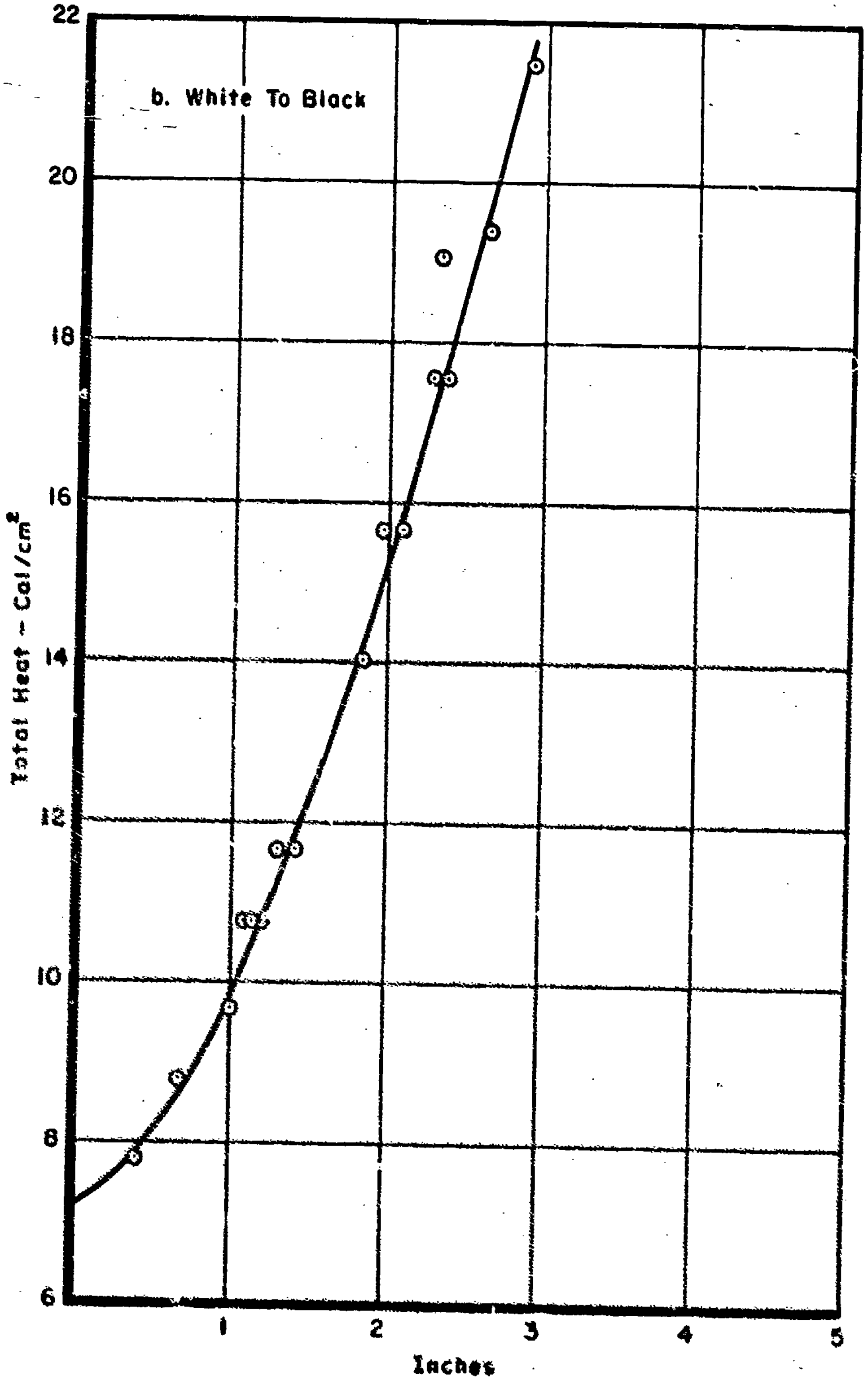


Figure 20 (Continued)

APPENDIX II

STATISTICAL ANALYSIS OF THREE-SECOND FIRE-PIT EXPOSURES SUMMER 1971

1. Mean in Percent Mannikin Damage for Nomex and for PBI

The first two entries in Column 1 of Table VIII represent the average percent mannikin damage for the Nomex and the PBI suits, respectively. If the Nomex and PBI data points are visualized as random samples, then these averages are unbiased estimates of the population means for percent body damage. The standard errors of the estimates and 90% confidence intervals for the population means are given in Columns 2 and 3 of Table VIII.

2. Relationship Between Percent Mannikin Damage and Calorimeter Reading

The data points for the Nomex and the PBI suits are plotted in Figures 21 and 22, respectively. The horizontal scale represents the calorimeter reading, and the vertical scale the percent mannikin damage. It was assumed that, for each fabric, the dependence of the mean in percent mannikin damage on the calorimeter reading can be represented by a third-degree polynominal. The least squares estimates of the regressions of damage on calorimeter reading are given, as well as the 90% confidence intervals for each of the points on the true regression lines.

TABLE VIII

MEAN PERCENT MANNIKIN DAMAGE

Parameter	Estimate	Estimated Standard Error of Estimate	90% Confidence Interval
Mean percent mannikin damage for Nomex Suit	49.8	4.25	49.8 ± 7.2
Mean percent mannikin damage for PBI Suit	28.4	4.20	28.4 ± 7.1
Mean difference			
Method a	21.4	2.83	21.4 ± 4.8
Method b	21.9	2.85	21.9 ± 4.9
Method c	20.5	3.61	20.5 ± 6.2

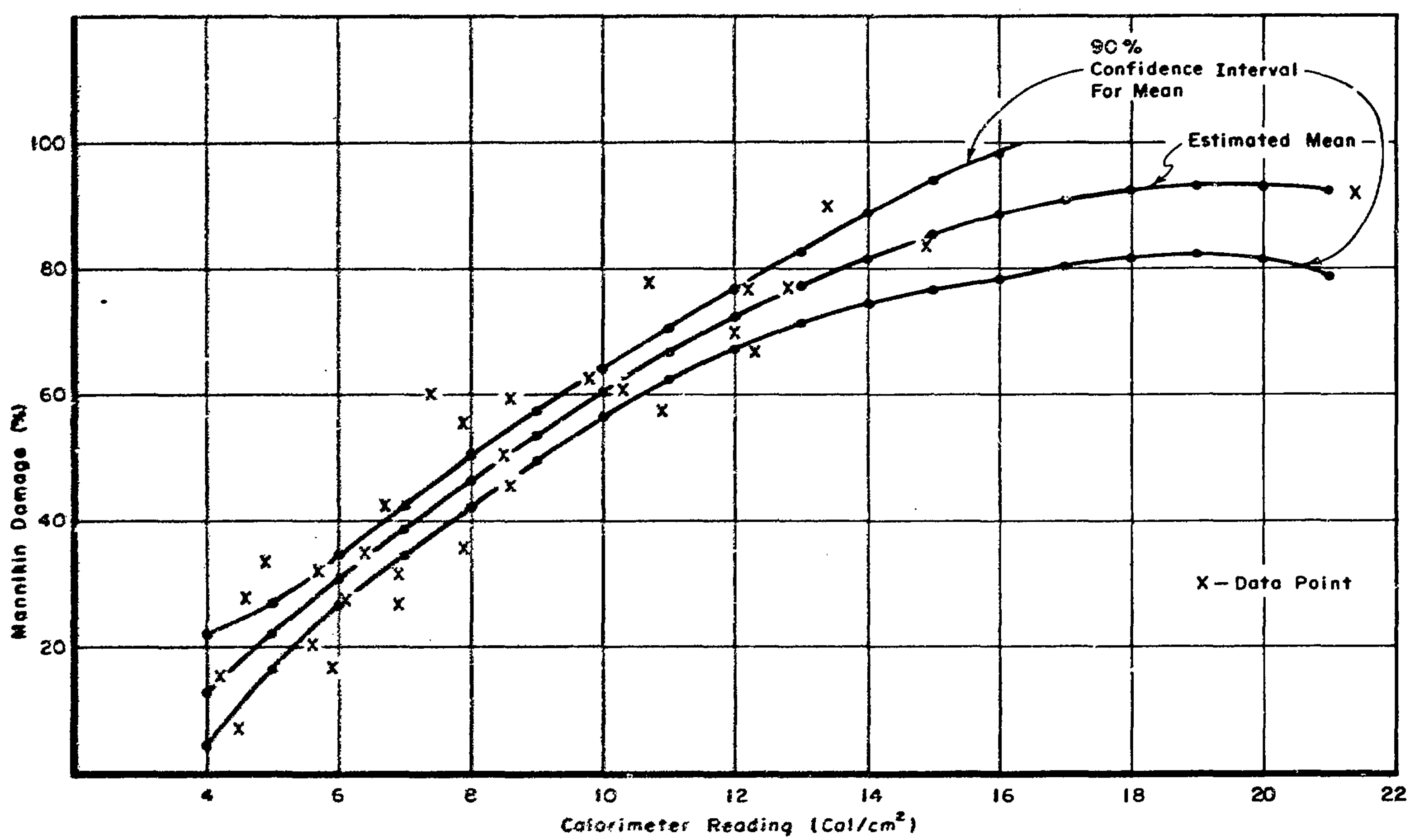


Figure 21. Estimated Mean in Percent Mannikin Damage for Nomex at Various Calorimeter Readings

DATA FOR FIGURE 21

cal/cm^2	Plotted point: lower curve	Plotted point: middle	Plotted point: upper	Data points: cal/cm^2	Data points: %
4	4.52	13.34	22.16	4.2	15.9
5	17.07	22.25	27.43	8.5	50.5
6	27.01	30.79	34.57	4.5	7.0
7	35.03	38.93	42.83	4.6	27.9
8	42.48	46.64	50.80	12.0	59.7
9	49.76	53.88	58.00	7.4	60.3
10	56.69	60.62	64.55	9.8	62.9
11	62.85	66.83	70.81	8.6	45.4
12	67.86	72.48	77.10	6.1	27.3
13	71.76	77.54	83.32	8.6	59.7
14	74.79	81.96	89.13	5.6	20.3
15	77.21	85.73	94.25	7.9	35.6
16	79.18	88.81	98.44	6.4	35.2
17	80.79	91.16		4.9	33.7
18	82.00	92.76		10.3	61.3
19	82.57	93.57		5.9	17.8
20	81.89	93.55		5.7	32.1
21	79.01	92.69		10.3	60.6
				13.4	89.9
				6.9	26.7
				7.9	55.9
				14.9	83.8
				12.2	76.8
				10.7	78.1
				6.9	31.7
				12.8	77.5
				21.4	92.1
				12.3	66.7
				10.9	57.8

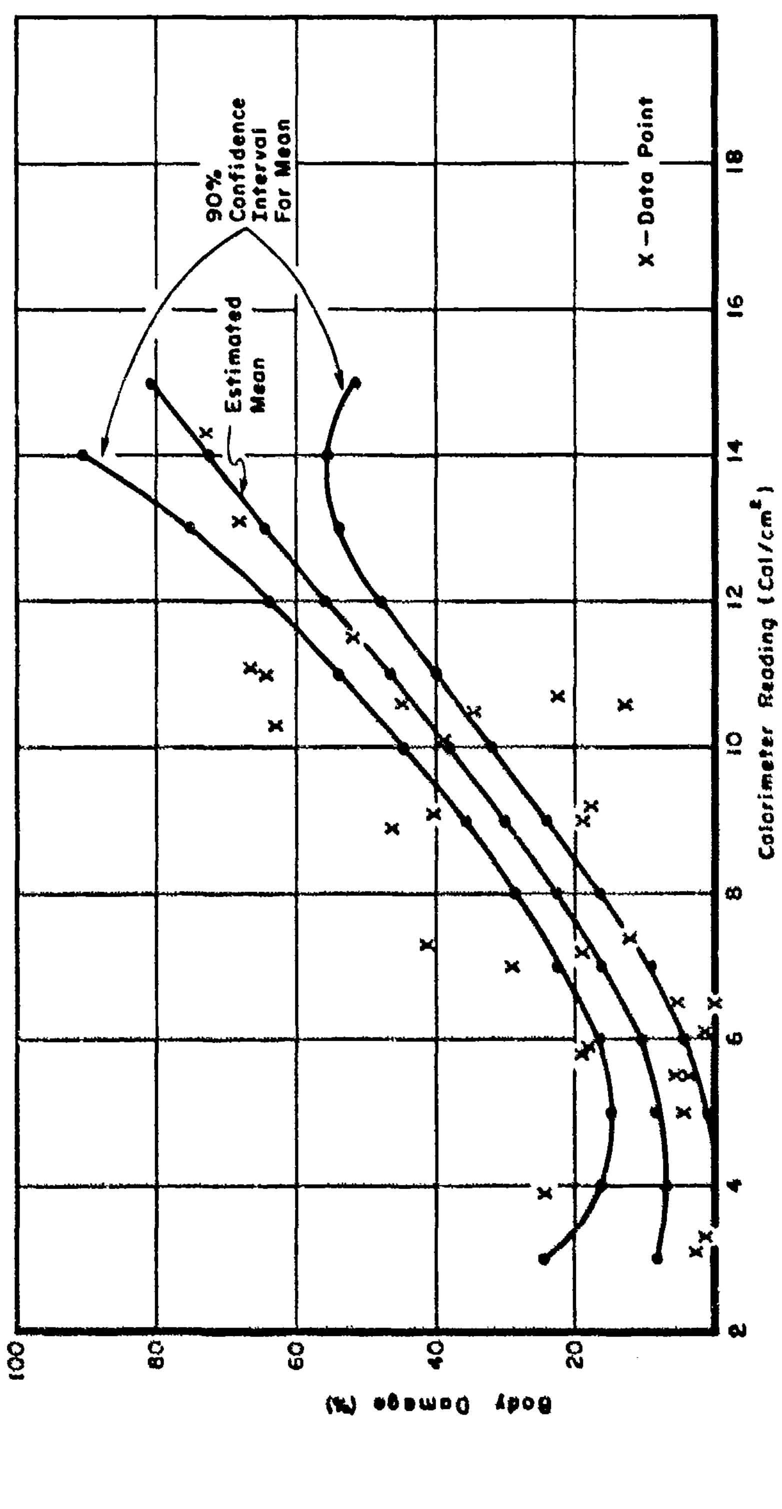


Figure 22. Estimated Mean in Percent Mannikin Damage for PBI at Various Calorimeter Readings

DATA FOR FIGURE 22

	Plotted point			Data points	
cal/cm	lower curve	middle	upper	cal/cm^2	%
3		8.20	24.45	5.5	3.8
4		7.08	16.17	7.2	19.1
5	1.25	8.26	15.27	9.2	17.8
6	4.47	11.45	18.43	5.5	5.4
7	9.67	16.35	23.03	9.9	46.1
8	16.59	22.66	28.73	5.8	19.1
9	24.22	30.07	35.92	10.7	22.5
10	32.00	38.30	44.60	7.3	41.3
11	40.00	47.03	54.06	4.9	18.1
12	47.92	55.96	64.00	7.4	12.1
13	54.00	64.81	75.62	3.9	24.1
14	55.74	73.27	80.80	3.3	1.3
15	51.72	81.03		6.5	0.0
				6.5	5.4
				9.1	40.3
				5.0	4.4
				3.1	2.5
				6.1	1.3
				10.1	38.7
				14.3	72.7
				9.0	19.1
				10.6	12.7
				13.1	68.3
				11.5	51.8
				10.6	44.8
				7.0	29.2
				11.1	66.7
				11.0	64.5
				10.5	34.3
				10.3	63.2

3. Dependence of the Difference in Percent Mannikin Damage Between Nomex and PBI Suits on the Calorimeter Readings

It was assumed that the observed difference in percent mannikin damage between the Nomex and the PBI suits on a given run, say the ith, can be represented by the model:

$$y_i = u_y + b_1(x_{1i} - u_x) - b_2(x_{2i} - u_x)$$
$$+ c_1(x_{1i}^2 - u_{x^2}) - c_2(x_{2i}^2 - u_{x^2})$$
$$+ a(x_{1i}x_{2i} - u_{x1x2}) + e_i;$$

where, visualizing the 30 runs as a random sample from a population of runs, y_i is the observed difference in percent mannikin damage; x_{1i} and x_{2i} are the observed calorimeter readings for the Nomex suit and PBI suit, respectively; and u_{x1x2} are the population means for y_i, for x_{1i} and x_{2i}, for x_{1i}^2 and x_{2i}^2, and for $x_{1i}x_{2i}$, respectively; b_1, b_2, c_1, c_2, and a core regression coefficients; and e_i is the observed value of a random error component. The above model can also be written

$$y_i = b_o + b_1x_{1i} - b_2x_{2i} + c_1x_{1i}^2 - c_2x_{2i}^2 + ax_{1i}x_{2i} + e_i,$$

where

$$b_o = u_y - (b_1 - b_2)u_x - (c_1 - c_2)u_{x^2} - au_{x1x2}.$$

We denote by $\hat{b}_o$, $\hat{b}_1$, $\hat{b}_2$, $\hat{c}_1$, $\hat{c}_2$, and $\hat{a}$, the least squares estimates of b_o, b_1, b_2, c_1, c_2, and a, respectively. Thus, the formula

$$\hat{b}_o + \hat{b}_1 x_1 - \hat{b}_2 x_2 + \hat{c}_1 x_1^2 - \hat{c}_2 x_2^2 + \hat{a} x_1 x_2,$$

gives an unbiased estimate of the expected difference in percent mannikin damage between a Nomex suit and a PBI suit, when their calorimeter readings have the values x_1 and x_2, respectively. In particular,

$$\hat{b}_o + (\hat{b}_1 - \hat{b}_2)x + (\hat{c}_1 - \hat{c}_2 + \hat{a})x^2$$

is an estimate of the mean difference when both calorimeter readings have the identical value x. This formula is plotted in Figure 23; 90% confidence intervals for these mean differences are also given.

4. Mean Difference in Percent Mannikin Damage Between Nomex and PBI.

Three different sets of estimates and 90% confidence intervals were provided in Table VIII for the expected difference in percent mannikin damage between Nomex and PBI suits. The sets have somewhat different interpretations.

a. In Method (a), the estimate is unbiased and the confidence statement correct when the 30 observed runs are regarded as a random sample from an overall population of runs. Here, the estimate is simply the average of the observed differences in percent body damage between Nomex and PBI over the thirty runs; i.e., the estimate is

$$\bar{y} = (1/30) \sum_{i=1}^{30} y_i.$$

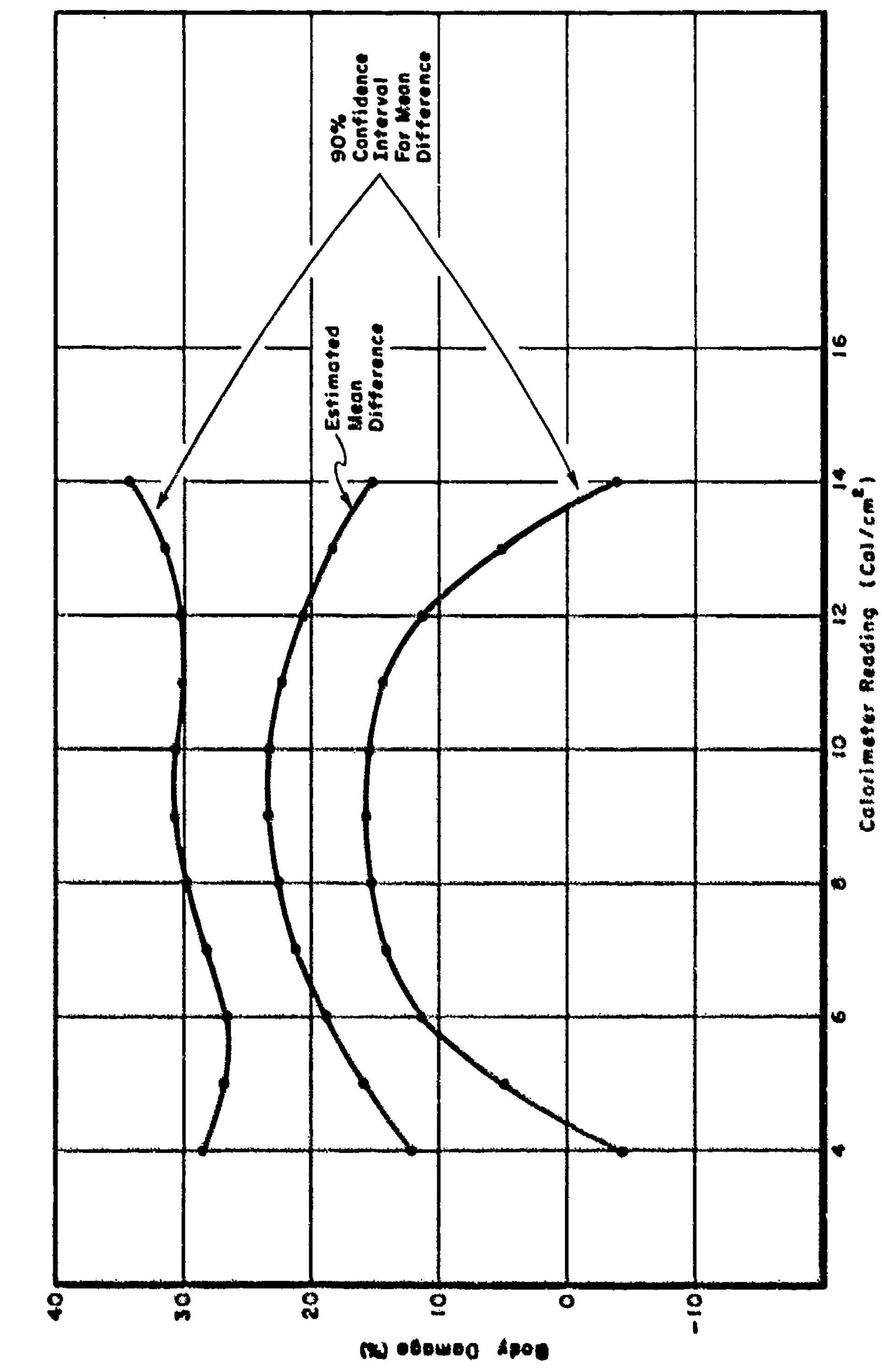


Figure 23. Estimated Mean Difference Between Nomex and PBI in Percent Mannikin Damage for Various Calorimeter Readings

DATA FOR FIGURE 23.

	Plotted point		
cal/cm	lower curve	middle	upper
4	-4.17	12.22	28.61
5	4.99	15.98	26.97
6	11.13	18.96	26.79
7	14.23	21.18	28.13
8	15.41	22.64	29.89
9	15.80	23.32	30.84
10	15.73	23.25	30.77
11	14.62	22.40	30.18
12	11.35	20.79	30.23
13	5.16	18.41	31.66
14	-3.85	15.26	34.37

We have the equality

$$\bar{y} = u_y + (b_1 - b_2)\left[\frac{\bar{x}_1 + \bar{x}_2}{2} - u_x\right]$$

$$+ (c_1 - c_2)\left[\frac{\overline{x_1^2} + \overline{x_2^2}}{2} - u_{x^2}\right] + \alpha\left[x\ \overline{x_1 x_2} - u_{x_1 x_2}\right]$$

$$+ \left[\frac{b_1 + b_2}{2}\right](\bar{x}_1 - \bar{x}_2) + \left[\frac{c_1 + c_2}{2}\right](\overline{x_1^2} - \overline{x_2^2})$$

$$+ (1/30)\sum_{i=1}^{30} e_i,$$

where $\bar{x}_1$, $\bar{x}_2$, $\overline{x_1^2}$, $\overline{x_2^2}$, and $\overline{x_1 x_2}$ represent the sample averages for x_{1i}, x_{2i}, x_{1i}^2, x_{2i}^2, and $x_{1i}x_{2i}$, respectively. Examination of this equality reveals that over a sequence of random samples having values of $\bar{x}_1$, $\bar{x}_2$, $\overline{x_1^2}$, and $\overline{x_2^2}$ identical to those actually observed, $\bar{y}$ is not an unbiased estimate of the overall population mean u_y. Rather, it is biased by an amount that depends on the differences $(\bar{x}_1 - \bar{x}_2)$ and $(\overline{x_1^2} - \overline{x_2^2})$.

b. Method (b) represents an attempt to circumvent this difficulty. Those runs on which the calorimeter readings differed by more than 3 calories/cm^2 were discarded (there were three of these) and the average of the remaining observed differences was taken to be the estimate of u_y. This procedure will generally reduce the bias described above; however, it may introduce other, probably smaller, biases.

c. In Method (c), we take our estimates of u_y to be

$$\hat{y} = \bar{y} - \left[\frac{\hat{b}_1 + \hat{b}_2}{2}\right](\bar{x}_1 - \bar{x}_2) - \left[\frac{\hat{c}_1 + \hat{c}_2}{2}\right](\overline{x_1^2} - \overline{x_2^2})$$

$$= b_o + \left[\frac{\bar{x}_1 + \bar{x}_2}{2}\right](\hat{b}_1 - \hat{b}_2) + \left[\frac{\overline{x_1^2} + \overline{x_2^2}}{2}\right](\hat{c}_1 - \hat{c}_2) + \overline{x_1 x_2}\hat{a};$$

i.e., we substract from $\bar{y}$ an estimate of the bias introduced by differences between Nomex and PBI in the observed calorimeter readings. Here, we estimate the standard error of y with respect to a sequence of random samples having values of $(\bar{x}_1 + \bar{x}_2)/2$, $(\overline{x_1^2} + \overline{x_2^2})/2$, and $\overline{x_1 x_2}$ identical to those actually observed, so that the 90% confidence interval is not one for u_y, but rather one for the expected difference in percent mannikin damage over this sequence. That is, we have placed a confidence interval on the mean difference in percent mannikin damage for a population in which the means of x_{1i} and x_{2i}, of x_{1i}^2 and x_{2i}^2, and of $x_{1i}x_{2i}$ are the values of $(\bar{x} + \bar{x}_2)/2$, $(\overline{x_1^2} + \overline{x_2^2})/2$, and $\overline{x_1 x_2}$, respectively, observed in the present fire-pit runs.

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13. ABSTRACT

Air Force flight suits made from PBI and Nomex fabrics were exposed to JP-4 liquid fuel fires to evaluate the thermal protection qualities offered to flight personnel. The two fabrics were compared on the basis of flammability, mechanical, and comfort characteristics. Thermal protection provided by the two materials was based on the mean difference in per cent body area damaged for sixty flight suits when exposed to a JP-4 fuel fire. PBI allowed twenty-one point five per cent less damage when compared to Nomex. PBI fabric in addition to providing thermal protection, has been proven in a full scale wear test to be the most comfortable flight suit fabric tested by the Air Force Operational Commands.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Flammability						
Flight Suits						
Heat Transfer						
Jet Fuel Fire						

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